Constructive Computer Architecture:

Guards

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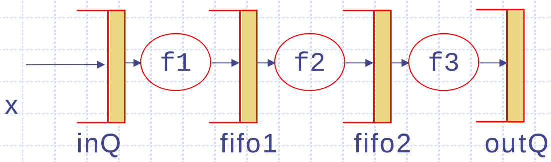
Elastic pipeline




```
rule stage1;
  if(inQ.notEmpty && fifo1.notFull)
    begin fifo1.enq(f1(inQ.first)); inQ.deq; end endrule
rule stage2;
  if(fifo1.notEmpty && fifo2.notFull)
    begin fifo2.enq(f2(fifo1.first)); fifo1.deq; end endrule
rule stage3;
  if(fifo2.notEmpty && outQ.notFull)
    begin outQ.enq(f3(fifo2.first)); fifo2.deq; end endrule
```

Proper use of FIFOs always involves checking for emptiness or fullness conditions

Easy mistakes

```
rule stage1;
  if(inQ.notEmpty && fifo1.notFull)
    begin fifo1.enq(f1(inQ.first);
          inQ.deq; end
endrule
```

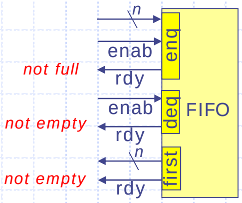
versus What is the difference?

```
rule stage1E;
  if(inQ.notEmpty && fifo1.notFull)
      fifo1.enq(f1(inQ.first);
  if(inQ.notEmpty) inQ.deq;
endrule
```

Guards is an abstraction to deal with such "atomicity" issues

stage1E may dequeue something even though the value read has not been processed (ie enqueued into fifo1)

FIFO Module: methods with guarded interfaces

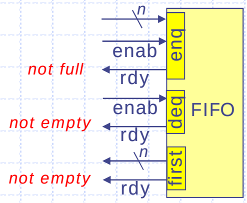



```
interface Fifo#(numeric type size,
                type t);
  method Action enq(t x);
  method Action deq;
  method t first;
endinterface
```

- Every method has a guard (rdy wire)
- The compiler ensures that an action method is invoked (en) only if the guard is true. Similarly the value returned by a value method is meaningful only if its guard is true
- Guards make it possible to transfer the responsibility of the correct use of a method from the user to the compiler
- Guards are extraordinarily convenient for programming and also enhance modularity of the code

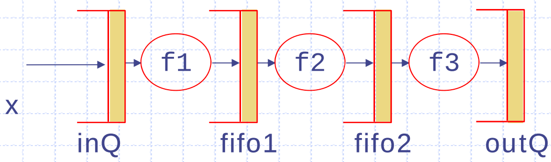
One-Element FIFO Implementation with guards

```
module mkCFFifo (Fifo#(1, t));
  Reg#(t)    d  <- mkRegU;
  Reg#(Bool) v  <- mkReg(False);
  method Action enq(t x) if (!v);
    v <= True; d <= x;
  endmethod
  method Action deq if (v);
    v <= False;
  endmethod
  method t first if (v);
    return d;
  endmethod
endmodule
```



Elastic pipeline

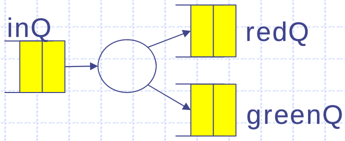
with guards




```
rule stage1 (True);   guard
  fifo1.enq(f1(inQ.first));
  inQ.deq();        endrule
rule stage2 (True);
   fifo2.enq(f2(fifo1.first));
  fifo1.deq;        endrule
rule stage3 (True);
  outQ.enq(f3(fifo2.first));
  fifo2.deq;        endrule
```

- When can stage1 rule fire?
  - inQ has an element
  - fifo1 has space
- The explicit guard is true but the compiler lifts all the implicit guards of the methods to the top of the rule

Switch with guards




```
rule switch (True);
  if (inQ.first.color == Red)
       begin redQ.enq  (inQ.first.value); inQ.deq; end
  else begin greenQ.enq(inQ.first.value); inQ.deq; end
endrule
```

```
rule switchRed (inQ.first.color == Red);
        redQ.enq(inQ.first.value); inQ.deq;
endrule;
rule switchGreen (inQ.first.color == Green);
        greenQ.enq(inQ.first.value); inQ.deq;
endrule;
```


GCD module

with Guards

```
Reg#(Bit#(32)) x <- mkReg(0);
Reg#(Bit#(32)) y <- mkReg(0);
rule gcd (x != 0);
  if (x >= y) begin
    x <= x – y; end
  else begin
    x <= y; y <= x; end
endrule
method Action start(Bit#(32) a, Bit#(32) b) if (x == 0);
  x <= a; y <= b; endmethod
method Bit#(32) result if (x == 0);
  return y; endmethod
```

If x is 0 then the rule cannot fire

- Start method can be invoked only if x is 0
- The result is available only when x is 0 is True.

All methods have implicit guards

- Every method call has an implicit guard associated with it
  - m.enq(x), the guard indicated whether one can enqueue into fifo m or not
- Methods of primitive modules like registers and EHRs have their guards always set to True
- Guards play an important role in scheduling; a rule is considered for scheduling only if its guard is true ("can fire")
- Nevertheless guards are merely syntactic sugar and are lifted to the top of each rule by the compiler

Information a guard carries can be encoded in a value method

Guard Elimination

Making guards explicit in compilation

- Make the guards explicit in every method call by naming the guard and separating it from the unguarded body of the method call, i.e., syntactically replace m.g(e) by

  $m.g_B(e)$ when $m.g_G$

  - Notice $m.g_G$ has no parameter because the guard value should not depend upon the input

Lifting implicit guards

```
rule foo if (True);
  (if (p) fifo.enq(8)); x.w(7)
```

All implicit guards are made explicit, and lifted and conjoined to the rule guard

```
rule foo if (p && fifo.enq_G || !p);
  if (p) fifo.enq_B(8); x.w(7)
```

```
rule foo if (fifo.enq_G || !p);
  if (p) fifo.enq_B(8); x.w(7)
```

Make implicit guards explicit

<a> ::= <a> | <a>
  | if (<e>) <a>
  | ~~m.g(<e>)~~ m.g_B(<e>) when m.g_G
  | let t = <e> in <a>

The kernel language with abstract syntax

<a> ::= <a> | <a>
  | if (<e>) <a>
  | m.g(<e>) methods without guards
  | let t = <e> in <a>
  | <a> when <e> guarded action

The new kernel language

We use "|" instead of ";" for parallel composition.
"|" and "::=" represent meta-syntax.

Syntax for guards

- rule x (g);
    a
  endrule
  is the same as rule x (a when g)
- method foo(x, y) if (g);
    a
  endmethod
  is the same as
    method foo(x, y) (a when g) endmethod
- If no guard is explicitly supplied, the guard is assumed to be True

Guards vs If's

- The predicate in a Conditional action only affects the actions within the scope of the conditional action

  (if (p1) a1) | a2

  p1 has no effect on a2 ...
- The guard on one action of a parallel group of actions affects every action within the group

  (a1 when p1) | a2

  ==> (a1 | a2) when p1
- Mixing ifs and whens

  (if (p) (a1 when q)) | a2

  ≡ ((if (p) a1) | a2) when ((p && q) || !p)

  ≡ ((if (p) a1) | a2) when (q || !p)

Guard Lifting Axioms

without Let-blocks

- All the guards can be "lifted" to the top of a rule
  - (a1 when p) | a2 ⇒ (a1 | a2) when p
  - a1 | (a2 when p) ⇒ (a1 | a2) when p
  - if (p when q) a ⇒ (if (p) a) when q
  - if (p) (a when q) ⇒ (if (p) a) when (q || !p)
  - (a when p1) when p2 ⇒ a when (p1 && p2)
  - m.g_B(e when p) ⇒ m.g_B(e) when p

similarly for expressions ...

- Rule r (a when p) ⇒ Rule r (if (p) a)

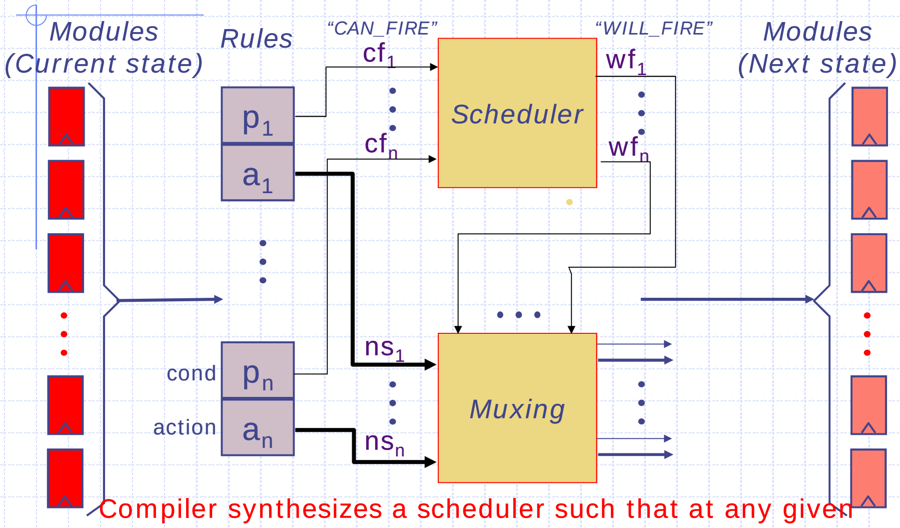
We will call this guard lifting transformation WIF, for when-to-if

A complete guard lifting procedure also requires rules for let-blocks

Scheduling with guards

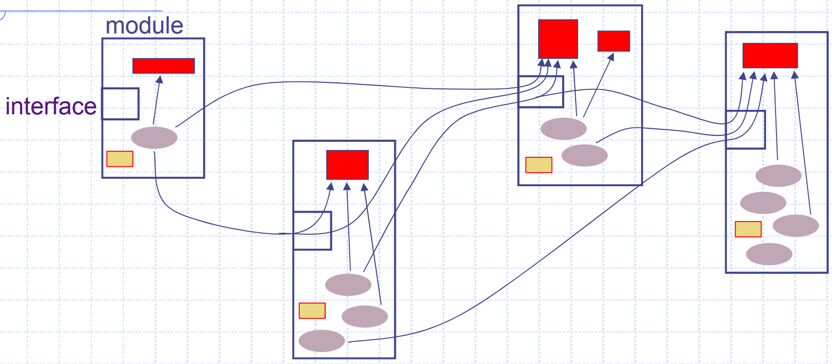
- At the top level a guard behaves just like an "if"
- A rule whose guard is False at a given cycle will result in no state change even if it is scheduled
- The guards of most rules can be evaluated in parallel, often with small amount of computation (The exceptions are 1. if two guards call the same method and the method has parameters; 2. if guards involve EHRs)
- The scheduler takes advantage of this fact by considering only those rules for scheduling in a given cycle whose guards are True

Scheduling and control logic



Compiler synthesizes a scheduler such that at any given time will-fire for only non-conflicting rules are true

Hierarchical scheduling



- According to Bluespec semantics, at most one rule from *any* module should execute in a given cycle
- Which module?
- Modules form a natural hierarchy;
  - Schedule inside out or outside in?

Hierarchical scheduling

- Scheduling is done outside-in:
- First, the rules of the outermost modules are scheduled, which may call (enable) methods of inner modules
- Then the rules of subsequent inner modules are scheduled, as long as they can be scheduled concurrently with the called methods
- BSV provides annotation to reverse this priority on a module basis
- It is because of scheduling complications that current BSV doesn’t allow modular compilation in the presence of interface parameters